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A combined experimental and numerical work was conducted on the interaction between finite span synthetic jets and a 3-D cross-flow. We completed a series of experimental and numerical simulations of the interaction of the synthetic jets with a cross-flow over unswept and swept configurations. The results show that the interaction results in the formation of secondary flow structures that enhance mixing and increase the efficiency of flow control. We publish our finding in a JFM paper, a Physics of Fluids paper, and we submitted another paper to Experiments in Fluids. One MS student graduated, and a PhD student also has been working on this project.

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**FUNDAMENTAL EXPERIMENTAL AND NUMERICAL INVESTIGATION OF ACTIVE CONTROL OF 3-D FLOWS**

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# FINAL REPORT


## ABSTRACT

A complementary experimental and numerical investigation was performed to study the 3-D flow structures and interactions of finite-span synthetic jets in a cross-flow at a chord-based Reynolds number range from 50,000 to 400,000 and angles of attack between $0^0$ to $20^0$. A range of momentum coefficients was considered corresponding to six different blowing ratios in the range of 0.2 to 1.2 with an increment of 0.2 (where, the blowing ratio is defined based on the averaged outstroke jet velocity to the free-stream velocity). Experiments were conducted on two finite wings (unswept and $30^0$ swept-back configurations) with a cross-sectional profile of NACA 4421, where both 2-D and stereoscopic PIV data were collected at various spanwise locations along the wing. In complement to the experiments, 3-D numerical simulations were performed, where the numerical setup not only matched the physical parameters (e.g., free-stream, blowing ratio, etc.) but also the physical dimensions (e.g., orientation and location of jet, flow control cavity including slot and chamber, etc.). Note that the numerical simulations only address one topic, which is the interaction of a single synthetic jet with a cross-flow over the unswept wing configuration, whereas the experiments included three sets of data: (1) a single finite span synthetic jet interacting with a finite unswept wing, (2) a single finite span synthetic jet interacting with a finite sweptback wing, and (3) multiple finite span synthetic jets interacting with a finite unswept wing.


## I. INTRODUCTION

The major goal in aerodynamics is to improve vehicle performance over a wide range of operating conditions. This can be achieved by optimizing the shape, or by using passive and/or active flow control techniques. Active flow control techniques based on fluidic actuators have been widely studied and used due to their dynamic applicability over a broad range of flow conditions along with their efficiency (e.g., separation mitigation at high angles of attack, virtual aero-shaping at low angles of attack, etc.). One approach is to couple the actuation frequency to instabilities inherent to separated flows and thus, alter the global flow field by modifying the large-scale vortical structures, e.g., Oster & Wygnanski (1982), Ho & Huerre (1984), Roberts (1985), Seifert et. al. (1993), Wygnanski (2000). In this approach, the time-period of actuation scales with the advection time through the length of the flow domain downstream of the separation (as measured by the reduced or non-dimensional frequency, $F^+$). In such an approach, control input is effective within a limited spatial domain immediately upstream of separation; however, when the flow is not separated (e.g., at low angles of attack) the efficacy of this approach is negligible (e.g., Seifert et al., 1993).

A different approach, where fluidic actuators that are driven at much larger frequencies than characteristic flow frequencies (such as synthetic jets, e.g., Amitay & Glezer, 2002a; Glezer et. al., 2005), allows more control through the modification of the apparent aerodynamic shape of the lifting surfaces (e.g., Amitay et. al., 1997; Amitay et. al., 2001b). This approach does not necessarily rely on coupling the actuation frequency to global flow instabilities and therefore, can be applied at various spatial locations and over a broader range of flow conditions (e.g., Amitay et. al., 2001a; Glezer & Amitay, 2002). Furthermore, it can accommodate a broader band control algorithms where more complex actuation waveforms can be used (e.g., the pulse modulation technique, Amitay & Glezer, 2006).

In the last decade a variety of promising flow control applications based on synthetic jet actuators have been presented. Several studies on synthetic jet applications have demonstrated that flow separation can be mitigated or even suppressed altogether (e.g., see Amitay et. al., 1999; Amitay & Glezer, 2002b; Crook et. al., 1999; He et. al., 2001). Synthetic jets have also been used for separation control in inlet ducts (e.g., Amitay et. al., 2002c). It has also been demonstrated on unmanned aerial vehicle (e.g., Parekh et. al., 2003), jet vectoring (e.g., Smith & Glezer, 2002) as well as for flight control on scaled models (e.g., Ciuryla et. al., 2007). More recently it has been used for vibration suppression in wind turbines by Maldonado et. al. (2009). Synthetic jets have also been applied at low angles of attack, where the flow is fully attached, for 2-D platforms (e.g., Chatlynne et. al., 2001; Amitay et. al., 2001a) and also for 3-D configurations (e.g., Farnsworth et. al., 2008). In some studies significant control forces were imparted by cropping the trailing edge of an airfoil and using synthetic jets (e.g., Timor et. al., 2007); which indicates an opportunity to replace the conventional control surfaces (e.g., flaps, aileron, rudder, etc.) with active flow control, or at least augment their performance in terms of control authority as well as frequency response.

Apart from such attractive synthetic jet based flow control applications, a large number of studies have been performed to investigate and characterize the flow structures and mechanisms due to synthetic jet actuation. These studies were experimental, computational or combined. More importantly, these investigations can be classified into two broad classes: (a) synthetic jets in quiescent conditions, and (b) synthetic jets in a cross-flow. Furthermore, these studies involved synthetic jets that were issued through orifices of different geometry ranging between: (i) plane 2-D or very high aspect ratio slits, minimizing the end effects (i.e., with aspect ratios of 75 or above), (ii) circular, elliptic or low aspect ratio ones (with aspect ratios below 5), and (iii) finite-span or rectangular slits with end effects (i.e., with aspect ratios between 5 and 75). Therefore, in the balance of this introduction three categories are considered and discussed: (1) synthetic jets in quiescent conditions (including circular, elliptic or rectangular slits covering full range of aspect ratios), (2) low aspect ratio synthetic jets in a cross-flow, and (3) finite-span rectangular synthetic jets in a cross-flow. The rational for this categorization is that the majority of the existing studies, to the best of the authors' knowledge, lie in the realm of the first two categories. On the other hand, flow structures formed due to the finite-span of rectangular synthetic jets can play an important role in various flow control applications (e.g., separation control, virtual aero-shaping, etc.) and require deeper understanding; therefore, it is the focus of the present work.

### *I.1 Synthetic Jets in Quiescent Conditions*

Smith & Glezer (1998) were the first to experimentally study the flow field of a synthetic jet in quiescent conditions (i.e., without a cross-flow). In their study, the jet was issued via a rectangular slit of a very high aspect ratio (i.e., 150). They showed, using spanwise flow visualization along the long axis of the slit, that periodically formed discrete vortex pairs undergo a transition to turbulence in a jet cycle and lose their coherence due to formation of instabilities in the form of spanwise-regular rib-like secondary vortical structures.

Numerical investigations of synthetic jet in quiescent conditions were performed by Kral et. al. (1997) and Lee & Goldstein (2002) based on 2-D simulations while Rizzetta et. al. (1999) performed high-resolution 3-D simulations. Note that in the 3-D simulations by Rizzetta et. al. (1999), the spanwise length of the slit was reduced by a factor of 10 as compared to the experiments of Smith & Glezer (1998) and furthermore, symmetry conditions at the jet centerline and mid-span were used to include only one quarter of the physical configuration; this was done due to limitation on computing resources. Two-dimensional simulations agreed with the experiments near the exit of the jets where the flow field was dominated by counter-rotating vortex pairs while farther away from the jet slit (i.e., after 10 slit widths) there was significant disagreement. On the other hand, 3-D simulations (by Rizzetta et. al., 1999) captured spanwise instabilities, which led the counter-rotating vortex pair to lose their coherence and breakdown farther downstream as was observed in the experiments (even though it was not possible in 3-D simulations to exactly duplicate the experimental configuration in terms of spanwise length of the jet slit). Mallinson et. al. (1999), Crook & Wood (2001), Cater & Soria (2002), and Zaman & Milanovic (2003) also made similar observations on 3-D flow structures and instabilities for synthetic jets issued through a circular orifice.

More recently, Yao et. al. (2004) conducted detailed experimental measurements of synthetic jets in quiescent conditions to be used for validation studies. The synthetic jet in this case had a rectangular slit with an aspect ratio of 28. Measurements were made using three different techniques, namely, Particle Image Velocimetry (PIV), Laser Doppler Velocimetry (LDV), and hot-wire anemometry; which included both near- and far-field measurements as well as measurements on two planes along and across the slit. They showed that besides the end effects at the edge of the jet slit, 3-D flow structures develop due to spanwise instabilities when the jet is advected downstream. They noted, as was done by Smith & Glezer (1998), that near the jet slit flow behavior is relatively smooth and uniform while the jet front develops wavy profiles downstream.

Numerical investigations for this case were done with varying degrees of success; which were based on 2-D and 3-D simulations. As before, in contrast to 2-D simulations, high-resolution 3-D simulations were able to capture spanwise instabilities in the form of rib-like secondary structures in the primary vortex pair, see Kotapati et. al. (2007) (they did not model the end effects by considering a jet along the entire span of the computational domain). Cui & Agarwal (2006) also performed 3-D simulations and included slot ends but showed limited agreement with the experiments which is possibly because the grid used was fairly coarse with only 29 points along the spanwise length of the slit (note that the aspect ratio of the slit is 28). For a detailed survey of simulations for this case see Rumsey (2009).

Amitay & Cannelle (2006) also carried out detailed experimental measurements for finite-span synthetic jets (i.e., issued via rectangular slits) in quiescent conditions, where they collected PIV data on two planes across and along the slit. They considered a range of orifice aspect ratios (from 50.8 to 101.6) and synthetic jet parameters (including stroke length and actuation frequency). Similar to earlier studies they showed that vortex pairs near the jet orifice are uniform and 2-D but farther downstream develop horseshoe-like patterns with secondary counter-rotating vortical structures along the span that form an array of streaks in the mean flow. They also showed the presence of edge-induced vortices due to the finite span of the slit as well as 3-D instabilities that prevail in the mid-span of the jet (even for a case with aspect ratio of 101.6; as was visualized by Smith & Glezer, 1998). Cannelle & Amitay (2007) extended these studies to investigate the transitory behavior of synthetic jets (following the onset and termination of the actuation), where they also made hot-wire measurements, and showed the formation, evolution and merging of vortices in the cross-stream and spanwise planes.

### *I.2 Low Aspect Ratio Synthetic Jets in a Cross-Flow*

In addition to detailed investigations of synthetic jets issued into a quiescent flow, the second category of studies involves synthetic jets in a cross-flow. Such studies, leading to understanding and characterization of flow structures and interactions due to synthetic jet actuation in the cross-flow, are critical for their effective application in flow environments of practical interest. Most of the studies on synthetic jets in a cross-flow have considered circular or elliptic orifices (with low aspect ratio). Crook & Wood (2001) used a water tunnel and studied an isolated circular synthetic jet in a cross-flow along with an array of synthetic jets on a tripped circular cylinder. In their experiments, they used dye visualization to show the 3-D interactions of vortical structures due to their tilting, stretching and mutual interaction. Similarly, Sauerwein & Vakili (1999) studied 3-D interactions of vortex rings for several synthetic jet configurations in a water tunnel. Gordon & Soria (2002) also used a water tunnel and carried out PIV measurements for a circular synthetic jet in a cross-flow. They considered only one measurement plane located at the center of the orifice and aligned with the cross-flow; based on this PIV data they observed deflection in the mean streamlines of the cross-flow to be up to 2-3 orifice diameters from the wall and for a distance up to 15-20 diameters.

Zaman & Milanovic (2003) used hot-wire anemometry in wind tunnel experiments to study a circular synthetic jet in a turbulent boundary layer and showed the formation of counter-rotating vortex pair, a region of low-momentum downstream to the jet (due to the blockage caused by the jet), and also high turbulence intensity regions. Milanovic & Zaman (2003) further extended their investigation to orifices of different geometries, including straight, tapered, pitched and clustered jet slots, all with the same cross-section at the slit. For the most part they observed similar flow structures between different orifices. The differences were in the jet penetration, which was somewhat smaller in the case of pitched and clustered orifices, and as expected, the pitched jet also lead to a region of high-momentum near the wall. In another study, Milanovic et. al. (2005) carried out a joint experimental and computational investigation of a straight circular synthetic jet in a cross-flow. They showed the overall agreement to be good in both axial and traverse planes but computational results over predicted the extent of the velocity deficit regions.

Schaeffler (2006) carried out detailed measurements, including LDV as well as planar- and stereoscopic PIV, for a circular synthetic jet in a turbulent cross-flow to be used as a validation database (similar to the case of a synthetic jet in quiescent conditions by Yao et. al., 2004). They showed same features of deflection in the mean streamlines of the cross-flow in the axial symmetry plane and counter-rotating vortex pair in the traverse plane. As before, follow up numerical studies, including 2-D and 3-D simulations, were carried out for this case. Three-dimensional simulations showed a reasonable qualitative agreement with experiments (e.g., see Xia & Qin, 2005; Cui & Agarwal, 2005; Dandois et. al., 2006); for a survey of numerical simulations for this case see Rumsey (2009).

Other detailed experimental studies on circular synthetic jets in a cross-flow were carried out recently by Jabbal & Zhong (2008), and Iai et al. (2009); all of which were conducted in a laminar or a low Reynolds number cross-flow. Jabbal & Zhong (2008) used a water tunnel to investigate the flow field of a circular synthetic jet on a flat plate. They carried out measurements based on stereoscopic dye visualization and thermochromic liquid crystal-based convective heat transfer sensing system to detect thermal footprints of passing flow structures. They identified three different types of vortical structures based on the range of blowing ratio, namely, hairpin vortices, stretched vortex rings, and tilted/distorted vortex rings. Furthermore, based on the thermal footprints of the flow structures they conjectured that either hairpin vortices or stretched vortex rings was responsible for the delayed separation on the circular cylinder studied by Crook et. al. (2001). Study by Iai et. al. (2009) was carried out in a fully developed low Reynolds number channel flow, which included a circular synthetic jet oriented either perpendicular to the cross-flow or with a $45^0$ pitch. Their measurements were based on scanning stereoscopic PIV system with multiple planes along the span to construct a 3-D flow field (similar to the technique used in the present study). One blowing ratio for both configurations of the synthetic jet was considered and formation of hairpin vortex structure was observed. As expected, in the inclined configuration asymmetry existed in the two longitudinal vortices of the hairpin structure.

More validations studies on the interaction of circular synthetic jets with a cross-flow include Zhou & Zhong (2009) and Wu et. al. (2009). Zhou & Zhong (2009) showed a good agreement with the laminar case of Jabbal & Zhong (2008), whereas Wu et. al. (2009) considered a turbulent cross-flow over a flat plate and showed a reasonably good agreement at downstream locations. Numerical studies were also carried out ranging from 2-D to 3-D simulations. For example, Mittal et. al. (2001) and Mittal & Rampunggoon (2002) performed 2-D simulations of synthetic jets in a laminar flow over a flat plate, and showed the existence of recirculation bubble in the mean flow near the orifice to demonstrate the virtual aero-shaping effect, whereas Ravi et. al. (2004) investigated effects of square and rectangular orifices (with aspect ratio up to 4) based on 3-D simulations; however, they presented limited results due to constraints on computing resources.

### *I.3 Finite-Span Rectangular Synthetic Jets in a Cross-Flow*

Smith (2002) performed wind tunnel experiments on an array of finite-span synthetic jets in a turbulent boundary layer (each jet had a rectangular orifice with an aspect ratio of 45). Two configurations of three parallel synthetic jets aligned in spanwise and streamwise directions on a flat plate were considered. All the measurements were based on hot-wire anemometry and therefore, it was noted that understanding 3-D flow structures in detail was difficult. Nevertheless, prominent features were shown, for example, spanwise configuration with an orifice normal to the cross-flow showed the blockage caused just upstream of the orifice along with a wake-like feature in the downstream region. Moreover, the orifice aligned in the streamwise direction exhibited longitudinal vortices embedded in the boundary layer.

Gilarranz et. al. (2005) also carried out wind tunnel experiments on finite-span synthetic jets (with an aspect ratio of 22.35) over a NACA 0015 wing with an aspect ratio of about 1 (end plates were used to minimize the 3-D effects due to finite span of the wing). They considered a high Reynolds number (i.e., 890,000) and varied angle of attack from low to high (i.e., -$2^0$ to $29^0$). Their results were based on force balance measurements, on-surface oil flow visualization, smoke flow visualization, surface pressure measurements, and wake surveys. Based on these measurements they showed significant effects due to synthetic jet actuation at high angles of attack, where the onset of stall was delayed from $12^0$ to $18^0$ and up to 80% increase in the lift coefficient was observed. They also showed a decrease in drag due to synthetic jet actuation. Recently, You and Moin (2008) numerically simulated this case at the same Reynolds number and at an angle of attack of $16.6^0$. In their 3-D simulations, they considered the jet slit to cover the entire span of the computational domain and thus, eliminating the end effects. They showed good agreement for the lift-coefficient and the wake. Furthermore, they presented phase-averaged velocity profiles, streamlines and pressure field, and also instantaneous iso-surfaces of vorticity, which helped in understanding the interaction of the jet with the cross-flow but without any end effects.

The motivation of the present paper is to extend the understanding of a finite-span synthetic jet interaction with a cross-flow; specifically, to investigate and explore the formation and evolution of secondary flow structures in the vicinity of the jet. In the current case, a low chord-based Reynolds number of 100,000 and $0^0$ angle of attack were selected. Also note that the jet was located near the leading edge at 17% of the chord (i.e., near the suction peak). Thus, the synthetic jet experienced a cross-flow with an oncoming boundary layer that was attached and laminar as it developed over the airfoil in a region with a strong favorable pressure gradient. Nevertheless, flow structures due to synthetic jet at high blowing ratio cases were found to be turbulent in downstream locations (as also seen without a cross-flow, e.g., Smith & Glezer, 1998; Rizzetta et. al., 1999; Amitay & Cannelle, 2006).

Complementary experimental and numerical studies were performed, where 2-D and stereoscopic PIV experimental measurements were carried out in the near vicinity of the synthetic jet for six different blowing ratios whereas high-resolution numerical simulations were performed for two blowing ratios (one in the lower range and one in the higher range). The resolution used in the current numerical simulations was adequate to resolve the physical scales well into the dissipation range in the vicinity of the jet, i.e., within the interrogation domain of interest direct numerical simulation (DNS) was applied, while far outside of the interrogation domain the mesh resolution was coarsened to one that is more typically used for large edge simulation (LES). Note that upstream of the jet the flow is laminar and transition is therefore captured with DNS resolution within the interrogation domain of interest that allows high confidence in the numerical simulation. Stabilized finite element methods like the one used here have been shown to be capable of handling both LES and DNS accurately (e.g., see Bazilevs et. al., 2007; Trofimova et. al., 2009). The primary focus of the current joint investigation was to provide a detailed and complementary understanding of the flow interaction, specifically in the vicinity of the synthetic jet, and as a necessary step to validate both techniques. One of the advantages of this complementary work includes availability of instantaneous and detailed 3-D flow fields (which are readily available from simulations) as well as long-time averaged fields (including both time-averaged or phase-averaged fields, which are easier to obtain from experiments). The broad goal of this on-going work is to understand the flow mechanisms associated with an array of synthetic jet actuators over true 3-D platforms (e.g., finite wings with sweep and/or taper). This knowledge can then be used to efficiently implement active flow control for flight control in lieu of, or in addition to, conventional control surfaces.

## II. EXPERIMENTAL SETUP

The experiments were conducted in an open-return wind tunnel at RPI, where the test section has a cross-section of 80*cm* x 80*cm* and is 457*cm* long. The models used in the experiments where finite wings with a constant chord, $c$ = 15.24*cm*, a span of $b$ = 40.64*cm* (resulting in an aspect ratio of 5.33), and a cross-sectional shape of NACA 4421 airfoil. A thick airfoil was selected such that it can be instrumented with multiple synthetic jet actuators. The models were divided into three sections along the span; each was instrumented with 15 synthetic jet actuators organized in three rows. Only the first row of jets was considered in the present study, which was centered at about 17% of the chord (from the leading edge). The spanwise spacing between side edges of subsequent jets in each row was 5.4*mm*. All jet orifices were oriented perpendicular to the surface and had a length of $L_z$ = 16*mm* (along the span), and a width of $h$ = 0.75*mm* (in the streamwise direction), leading to an aspect ratio of 21.33. Each jet consisted of a discrete cavity and a single piezoelectric disk that was mounted in the side opposite to the orifice..

The three model sections (made by stereolithography) were attached to an aluminum skeleton. In addition, a circular fence was placed at the root of the wing to isolate the model from the tunnel wall boundary layer. Each wing assembly was attached to a motor-driven pitch mechanism to enable a precise control of the angle of attack. The entire assembly was mounted in upside down configuration on one of the side walls of the wind tunnel to allow the NG-YAG laser for the PIV system to issue from below the tunnel, as the top of the tunnel is not optically accessible. CCD cameras were mounted on an optical table; one for the 2-D PIV and two for stereoscopic PIV. The cameras were aligned perpendicular to the laser light sheet to allow for streamwise planes to be acquired.

The PIV system used was a commercial LaVision system of hardware and software including two 120 mJ Nd:YAG lasers and two 1376 x 1040 pixel resolution thermo-electrically cooled 12-bit CCD cameras. Cylindrical lens was used to create the light sheet and a focal lens was used to focus the sheet at the measurement domain. The laser light sheet was then aligned with the area of interest using a computer-controlled three axis traversing system mounted below the test section. The flow was seeded with O($1\mu m$) water-based smoke particles, generated by a theatrical fog machine. The velocity components ($U$, $V$, $W$) were computed from the cross-correlation of 500 pairs of successive images.

Data on multiple spanwise planes (1*mm* or 2*mm* apart) were acquired along the central region of the span (i.e., center jet in the middle module. Stereoscopic PIV data collected on these planes were within a window size of about 25*mm* x 25*mm* (for the unswept model) and 40*mm* x 40*mm* (for the sweptback model). The data from all the planes were then reconstructed into a volume to provide the 3-D interaction domain between the synthetic jets and cross-flow.

In the experiments, six actuation levels were selected (in addition to the baseline case), where momentum coefficient ranged from $3.96 \times 10^{-4}$ to $1.42 \times 10^{-2}$ (corresponding to a range of blowing ratios from 0.2 to 1.2 with an increment of 0.2. Furthermore, a frequency of 2,500*Hz* was selected as the driving frequency for the jets (where all the jets produced the same velocity and they all operated in-phase). Note that the characteristic frequency of the flow over the airfoil (based on the "time of flight") is about 66*Hz*, and thus, the actuation frequency is more than an order of magnitude higher, which, as will be shown later, results in a virtual aero-shaping of the wing.

## III. NUMERICAL SETUP AND METHODOLOGY

In addition to the experiments, 3-D flow computations were carried out for a single finite-span synthetic jet flush mounted on the surface of a unit wing section. The numerical setup not only matched the physical parameters (e.g., free-stream, blowing ratio, etc.) but also the physical dimensions (e.g., width and aspect ratio of the jet slit, orientation and location of jet, flow control cavity including slot and chamber, etc.). Numerical simulation of two actuated cases were performed; one corresponding to $C_{\mu c}$ = $1.58 \times 10^{-3}$ or $C_b = 0.4$ (i.e., in the lower range where non-negligible effects due to jets were observed experimentally), and another corresponding to $C_{\mu c} = 1.42 \times 10^{-2}$ or $C_b = 1.2$ (i.e., the highest actuation level); these cases are referred to as $C_{\mu c2}$ and $C_{\mu c6}$, respectively.

The computational configuration, including boundary conditions and geometric details where the flow control cavity includes the slot and chamber with the diaphragm surface at the opposite end (matching the experimental setup). The boundary conditions were applied as follows: (1) free-stream velocity was prescribed at the tunnel inlet, (2) upper and lower tunnel walls (about four chord lengths from the airfoil) were considered as impenetrable or slip walls, (3) symmetry boundary conditions were used at the side surfaces (not shown in figure), (4) airfoil and cavity surfaces (except diaphragm) were considered as no-slip walls, (5) at the circular diaphragm a velocity profile was applied to match the disk motion, and (6) ambient pressure was prescribed as a natural boundary condition at the tunnel outlet. Note that the displacement of the actuator diaphragm was not modeled in the simulations; instead, a parabolic velocity profile (along the radius of the diaphragm) with a sinusoidal variation in time was prescribed such that both the amplitude (for each different momentum coefficient) and frequency (fixed at 2500*Hz*) matched with the experiments. The velocity amplitude was determined based on the hot-wire data collected at the center of the jet exit without a cross-flow. Note that in the simulations only a single synthetic jet in the span was considered; as it was determined experimentally that the flow is quasi-periodic along the mid-span section of the wing.

The numerical simulations solved the incompressible Navier-Stokes equations. Spatial discretization was carried out with a stabilized finite element method (i.e., Streamline/Upwind Petrov-Galerkin (SUPG) method) while temporally implicit integration was performed based on a generalized-alpha method. The resulting non-linear algebraic equations were linearized to yield a system of equations, which were solved using iterative procedures, e.g., GMRES. Furthermore, mesh resolution was increased in an adaptive fashion since for problems of practical interest, increasing the mesh resolution to a level necessary for acceptable accuracy in a globally uniform fashion would introduce prohobitive demands on the computational resources. In adaptive mesh methods, mesh resolution and configuration are determined and modified in a local fashion based on the spatial distribution of the numerical solution and approximation errors associated with it.

In this study, we employed boundary layer mesh adaptivity (Sahni et. al., 2008) that maintains favorable attributes of such meshes, i.e., high-aspect ratio, orthogonal, layered and graded elements near the viscous walls. In each actuated case, four mesh adaptation iterations were carried out, which resulted in an adequate mesh with about 11.5-15 million nodes and 65-80 million elements. Implicit time integration was performed with 360 time-steps of constant size in each jet cycle (computations with 180 time-steps in a cycle showed no significant differences).

## IV. RESULTS AND CONCLUSIONS

As mentioned above, multiple synthetic jets/cross flow combinations were tested. For brevity, a few sample results are presented; for a detailed information of the work conducted under this grant, see our publications:


1. Y. Elimelech, J.D. Vasile, and M. **Amitay**, "Secondary Flow Structures due to Interaction between a Finite-span Synthetic Jet and a 3-D Cross Flow", *Physics of Fluids*, **23**, September, 094104 (2011); doi:10.1063/1.3632089 (*13 pages*)
2. O. Sahni, J. Wood, K. E. Jansen, and M. **Amitay**, "3-D Interactions between a Finite-Span Synthetic Jet and a Cross Flow at a Low Reynolds Number and Angle of Attack", *Journal of Fluid Mechanics*, Volume 671, pages 254-287, 2011.
3. J. Vasile, Y. Elimelech, and Michael Amitay, "Flow Interactions of Finite Span Synthetic Jets and a Cross-flow", 51st *Israel Annual Conference* on Aerospace Sciences, Haifa, Israel, February 2011
4. J. Vasile, Y. Elimelech, J. Farnsworth, M. Amitay, and K.E. Jansen, "Interaction of a Finite-span Synthetic-jet and Cross-flow over a Swept Wing", *AIAA conference*, Chicago, IL, AIAA 2010-4584
5. J. Wood, O. Sahni, K. Jansen and M. Amitay, "Experimental and Numerical Investigation of Active Control of 3- D Flows", *AIAA conference*, San Antonio, TX, June 2009. AIAA-2009-4279
6. J. Vasile and Michael Amitay, "Interactions of Finite Span Synthetic Jets and a Cross-flow", to be submitted to *Experiments in Fluids*, October 2011

## IV.1 Interactions of a single finite span synthetic jet with a flow over an unswept finite wing

The interaction of a finite-span synthetic jet with a cross-flow over a finite wing at a chord-based Reynolds number of 100,000, and $0^0$ angle of attack, was studied experimentally and numerically. Experiments were conducted on a finite wing with a cross-sectional profile of NACA 4421, where a range of momentum coefficients was considered corresponding to six blowing ratios in the range from $C_b$ = 0.2 to $C_b$ = 1.2 (with an increment of 0.2). Numerical simulations of two actuated cases were performed; one corresponding to $C_b$ = 0.4 (in the lower range where non-negligible effects due to synthetic jets were observed experimentally), and another corresponding to $C_b$ = 1.2 (i.e., the highest actuation level).

A detailed comparison between experimental and numerical results was presented based on the time-averaged and phase-averaged flow fields at different locations including along normal-to-the-surface lines and across the center-plane. Furthermore, since 3-D measurements were made experimentally a volumetric comparison was also performed in a spanwise strip covering the full span of the synthetic jet. In all cases, good agreement was shown between the experimental measurements and numerical results but there were some limitations. For example, PIV data were not available very close to the surface whereas phase-averaged numerical data based on 350 jet cycles appeared to be noisy in the high blowing ratio case. Furthermore, in the low blowing ratio the resolution of experimental data in the span was limited whereas in the high blowing there were discrepancies in velocity profiles immediately downstream to the jet exit and very near to the surface. Nonetheless, the joint investigation provided a detailed and complementary understanding of the flow interaction by taking advantage of the strength of each technique, e.g., long-time averaged data from experiments whereas high-resolution temporal and spatial data from simulations. Agreement on quantities that both can obtain was used to validate both the techniques.

In addition to a detailed comparison, 3-D interactions between the finite-span synthetic jet and cross-flow were analyzed based on time-averaged, phase-averaged and instantaneous flow fields. Experiments provided results for six different blowing ratios (Figure 1) while simulations complemented with detailed spatial and temporal data (as high-resolution 3-D instantaneous and averaged flow fields were available from current numerical simulations), See Figure 2.

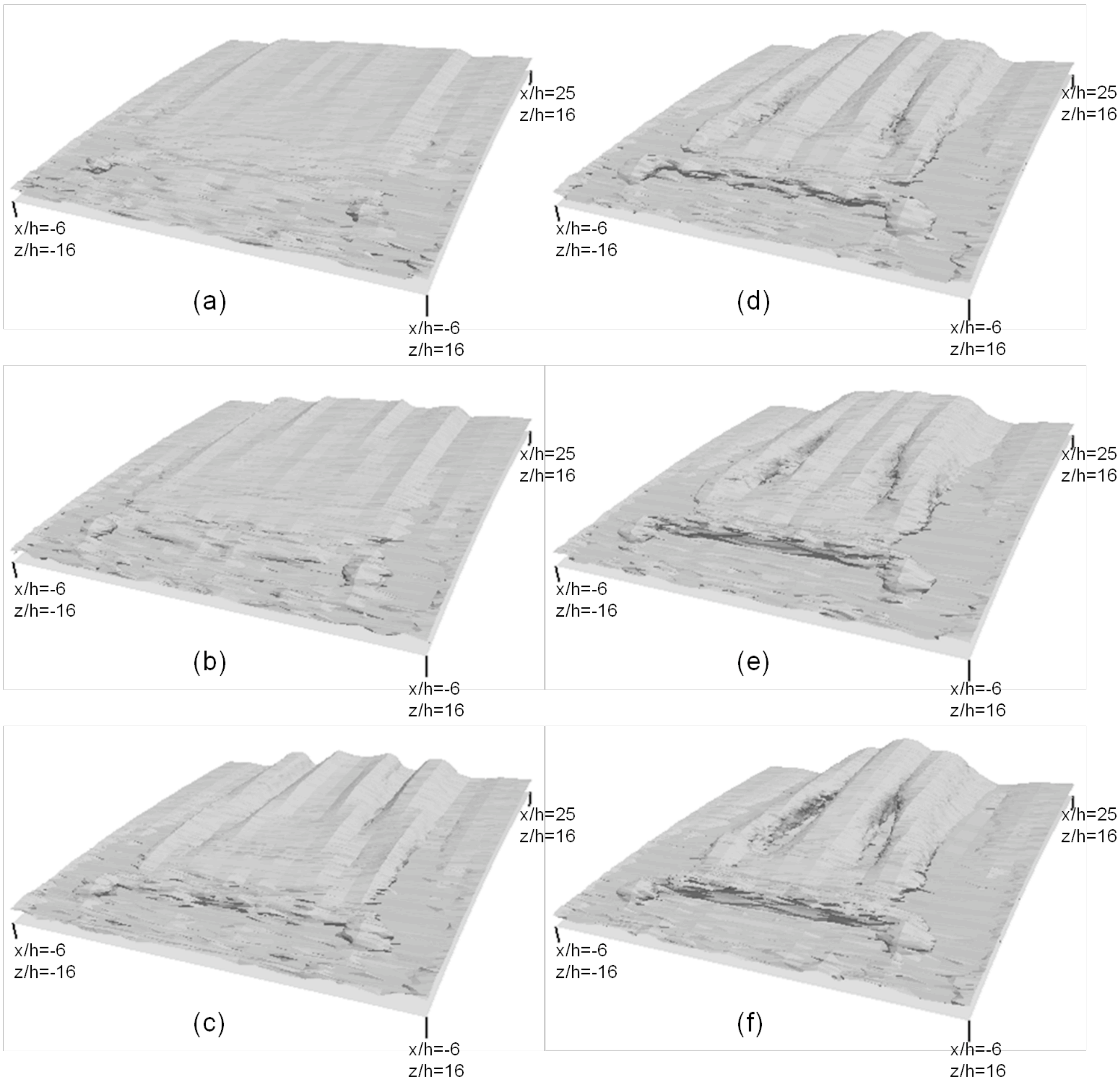


**Figure 1**: Effect of the momentum coefficient on the time-averaged (volumetric) flow field; **experimental data** for six actuated cases; $C_b$ = 0.2 (a), 0.4 (b), 0.6 (c), 0.8 (d), 1.0 (e), and 1.2 (f). Iso-surface of total velocity at $U/U_\infty = 1.3$.

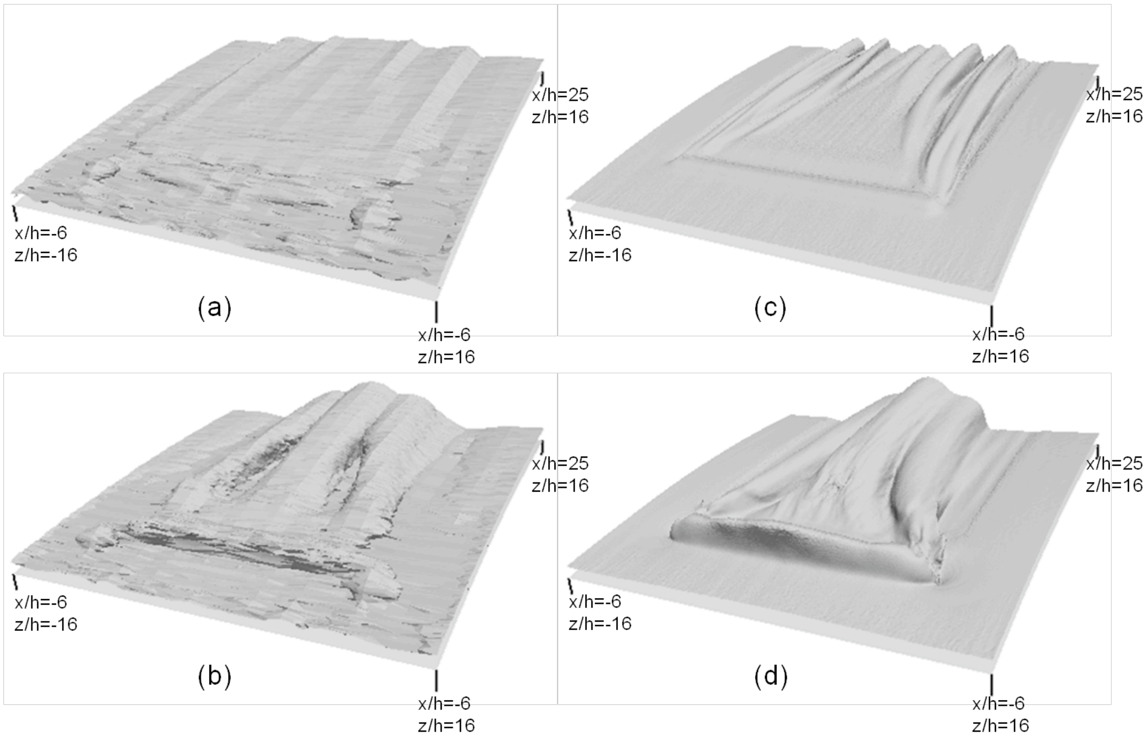


**Figure 2**: Time-averaged iso-total velocity surface at a level of $U/U_\infty = 1.3$ (note that no relative scale factor is applied between different coordinates). **Experiments** (a, b) and **simulations** (c, d) for forced cases with $C_b = 0.4$ (a, c) and 1.2 (b, d).

Emphasis was placed on flow structures along with their interactions and evolution in the vicinity of the synthetic jet. It was found that in the low momentum coefficient cases, 2-D spanwise rollers formed near the slit in each jet cycle; however, due to the finite-span of the slit streamwise vortices developed at the edge of the slit. Furthermore, the cross-flow accelerates around the edge of the slit and develops spanwise velocity components. Due to which the 2-D spanwise rollers are perturbed leading to formation of small and organized secondary flow structures farther downstream in the form of multiple distinct streak-like flow structures in the mean flow. On the other hand, in the high blowing ratio cases turbulent vortical structures were dominant that lead to larger spanwise structures, or lobe-like pattern, in the mean flow, where three-dimensionalities were formed immediately downstream of the jet slit. Comparison of instantaneous and phase-averaged flow fields clearly showed the presence of significant turbulent motions (in contrast to the low blowing ratio case). In all cases the spanwise extent of the coherent structures reduced with downstream distance; the decrease was more for cases with higher blowing ratio. Similar flow patterns were observed in earlier studies on finite-span synthetic jets without a cross-flow, e.g., Amitay & Cannelle (2006).

Spatial and temporal evolution of flow structures were also studied with the help of cross-stream planes at different locations, and phase-averaged flow fields at six different phases. It was found that in low-range cases (with $C_b$ = 0.2 and $C_b$ = 0.4) well-organized structures existed in the form of multiple distinct streamwise-oriented secondary vortical structures. In the mid-blowing ratio range, combined features of the low-range (near the slit) and high-range (in downstream locations) were found and the pair of counter-rotating vortices issued in the same jet cycle collided with each other. In the high-bowling ratio range, a train of counter-rotating coherent vortices existed that lifted-off the surface as they advected downstream.

## IV.2 Secondary Flow Structures Due to Interaction Between a Finite-Span Synthetic Jet and a Cross Flow over a Swept-back Finite Wing

The interaction of a finite-span synthetic jet with a cross-flow over a low aspect ratio and swept-back configuration was studied experimentally at a Reynolds number of $10^5$ and two angles of attack. The focus of this work was to explore the interaction of a finite span synthetic jet with a locally attached or separated flow field in the vicinity of the synthetic jet orifice. The effect of two different blowing ratios was discussed in details. As was shown in our previous work for an unswept finite configuration, the time-averaged velocity field exhibits secondary streamwise flow structures that evolve due to the finite span of the synthetic jet orifice. That work also showed that the spanwise spacing between these streamwise structures decreases as the blowing ratio increases. The phase-averaged measurements over the swept-back finite configuration showed that in the presence of sweep the flow becomes highly three-dimensional almost immediately downstream of the synthetic jet orifice (Figure 3). It is hypothesized that the baseline flow field that develops over a swept-back configuration, which is characterized by spanwise and streamwise vorticity components, is responsible for the immediate breakdown of the coherent structures that are introduced by the synthetic jet orifice, and for the formation of the secondary flow structures that were seen in the time-averaged flow field.

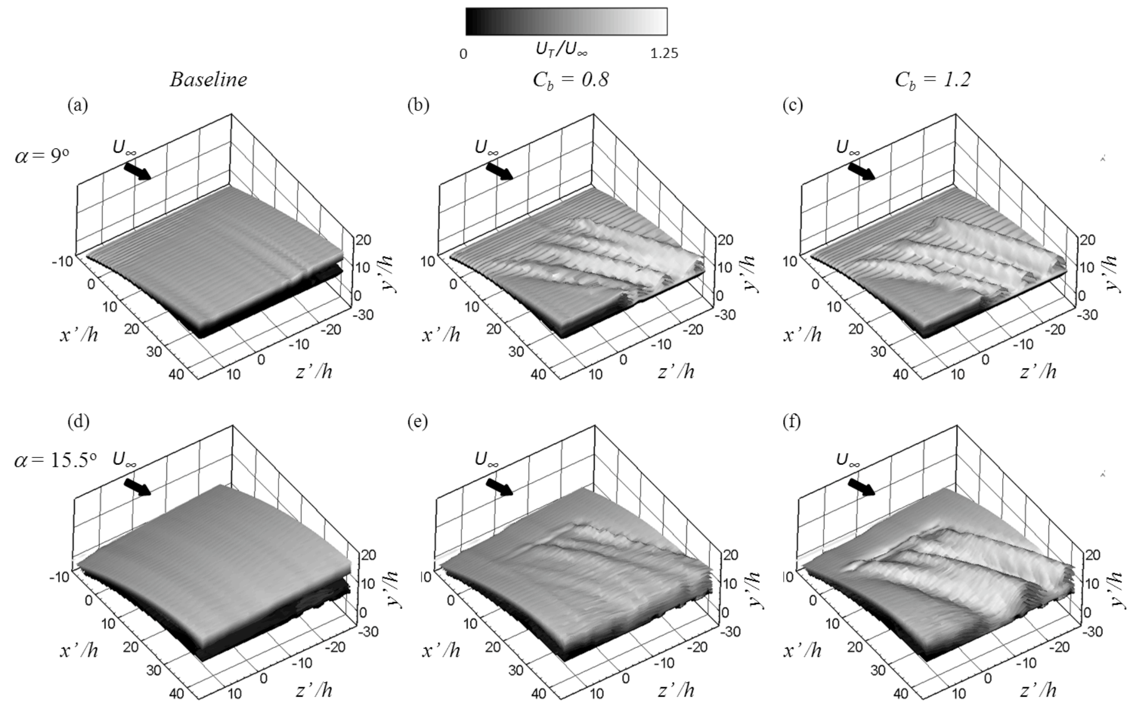


**Figure 3: Experimental** iso total velocity surfaces at $\alpha$ = 9° (a-c) and 15.5° (d-f); baseline (a, d), and forced with $C_b$ = 0.8 (b, e) and 1.2 (c, f).

## IV.3 Interaction Between multiple Finite-Span Synthetic Jets and a 3-D Cross Flow

The interaction of several finite span synthetic jets with a cross-flow over a low aspect ratio and swept wing was studied experimentally at a Reynolds number of $10^5$ and an angle of attack of 13.5°. The focus of this work was to explore the interaction of an array of up to three finite span synthetic jets with a flow over a swept back finite wing, especially the formation and advection of secondary flow structures in the vicinity of the synthetic jets for different jets combinations. As was shown in our previous work on the interaction of a single synthetic jet with the cross flow over a swept wing, the time-averaged velocity fields exhibited streamwise flow structures that evolved along the jet's orifice span.

Stereoscopic PIV data were collected across the three jets in the mid-span section, where the effect of the jets' location, number of jets used, and their blowing ratio ($C_b$ = 0.8 and 1.2) was analyzed based on the three-dimensional flow field using time-averaged and phase-averaged statistics. The arrangement of synthetic jets was investigated through the use of varying actuation combinations in order to fully understand the interaction of the jets with the cross flow. In order to capture and analyze the secondary flow structures, three cases were studied in more details: (1) only the center jet was activated, (2) the two synthetic jets off the middle jet were activated, and (3) all three synthetic jets were actuated. In the present study, the wing was placed at an angle of attack of 13.5°, in which the boundary layer was either attached in the vicinity of the middle synthetic jet or partially separated (i.e., separation bubble) in the vicinity of the jet closer to the wing tip. As was shown in our previous work on the interaction of a single synthetic jet with the cross flow over a sweptback wing, the time-averaged spanwise vorticity fields exhibited streamwise flow structures that were formed along the jets orifice span and advected downstream. Through the use of time-averaged and phase-averaged data measurements, it was shown to confirm the previous findings of the presence of secondary tilted structures. Furthermore, it was demonstrated that the synthetic jet effect is experienced spatially in both the vicinity, as well as farther away of the jets' locations (Figure 4).

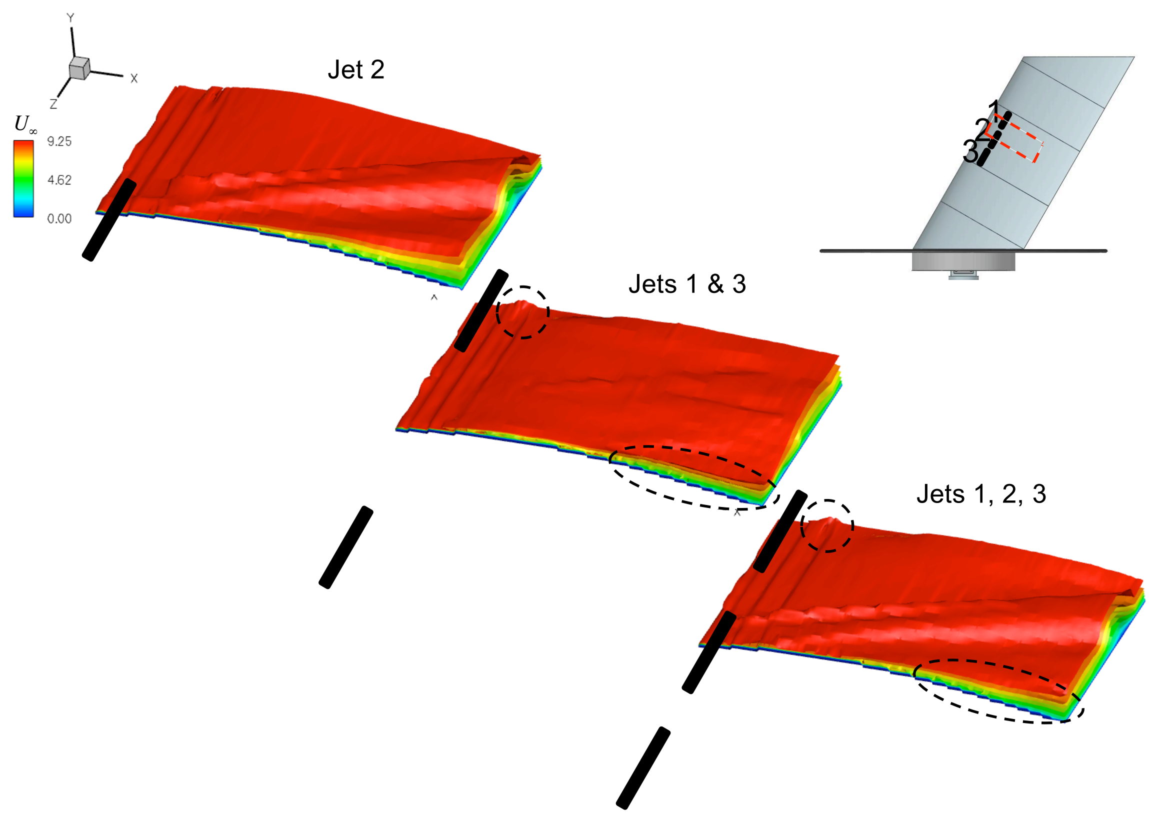


**Figure 4: Experimental** iso total velocity surfaces at $\alpha = 13.5^o$ with $C_b = 1.2$. Effect of different jets combinations on the mean flow over the wing.

## V. LIST OF PEOPLE INVOLVED IN THE PROJECT

During the 3-year project people were involved in the work, including Joshua Wood (graduated with MS), Joseph Vasile (a PhD student), Yossef Elimelech (post-doctoral fellow), Onkar Sahni (research engineer), and the two PIs of the project: Profs Ken Jansen and Michael Amitay.

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